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DURING PLASTIC DEFORMATION OF ALUMINUM

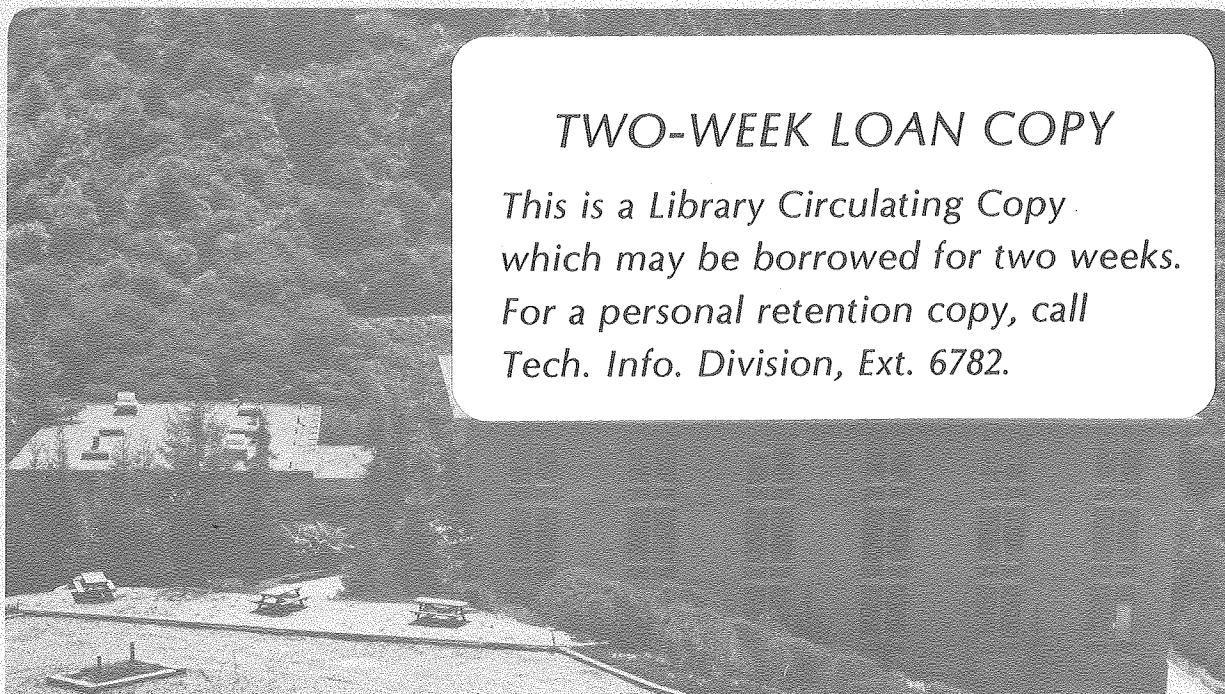
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EFFECT OF GRAIN SIZE ON THE ACOUSTIC
EMISSION GENERATED DURING PLASTIC DEFORMATION
OF ALUMINUM

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SUMMARY

Acoustic emission signals from polycrystalline Al 1100 samples during plastic deformation were analyzed with respect to the strain rate and grain size. A kinematic model is proposed to account for the observed behavior. An experimental acoustic emission parameter, equivalent to the average energy of the acoustic events, correlates satisfactorily with the computed energy of moving dislocations during the deformation process. Both energies attain a maximum value for a certain grain size, and are directly dependent on the strain rate.

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1. INTRODUCTION

Acoustic emission is defined as the generation of stress waves by a material undergoing abrupt structural rearrangement. The emission is supposed to have strong correlation with the dislocation kinetics. Several publications have appeared during the last years [1,2] dealing with dislocation velocities and mobile dislocation densities, and attempting to correlate these properties with fundamental deformation processes, such as microyielding, Lüders band motion, strain hardening, grain boundary sliding or microcrack nucleation.

Eshelby [3] has shown that a dislocation in motion radiates energy similarly to an accelerated electrical charge. Mirabile [4] has derived a dislocation Poynting vector indicating that processes like acceleration, deceleration and arrest, causing a change in the state of dislocation motion emit energy of given amount which can be detected at the surface of the specimen.

The objective of the present study is to correlate acoustic emission data obtained during plastic deformation of polycrystalline aluminum, of different grain sizes and at various strain rates, with the energy release due to acceleration and deceleration of moving dislocations.

2. EXPERIMENTAL

Polycrystalline, commercial-grade Al-1100 sheet, was used to prepare flat tensile specimen with the following gauge dimensions: 5 cm long, 1.25 cm wide, and 0.2 cm thick in the gauge section. The chemical composition of the material is given in Table 1. A controlled recrystallization procedure, Table 2, was applied in order to obtain a

variety of grain sizes, in the range between 40 and 120 μm . The grain size was determined by employing the standard ASTM procedure. Typical grain sizes are shown in Fig. 1. The samples were water-cooled after the heat treatment. Prior to tensile testing, the specimens were chemically cleaned in order to remove superficial oxide films.

Plastic deformation was performed employing an INSTRON tensile testing machine, at different crosshead velocities, and up to stresses equivalent to 90% of the UTS, for each grain-size. Strain was determined by a 25% gauge elongation extensometer, and simultaneously chart-recorded with the applied stress. Crosshead velocities during unloading were 1/10 of the velocities during loading. The strain-rates, $\dot{\epsilon}$, were 3.3×10^{-3} and $6.6 \times 10^{-3} \text{ sec}^{-1}$ for all samples. The 70 μm grain size sample were also stressed at rates of 1.6×10^{-3} and $1.33 \times 10^{-2} \text{ sec}^{-1}$. The yield point, σ_{yp} , was determined for each test.

Acoustic emissions were picked up by a piezoelectric transducer resonant on the 150-300 kHz range. The transducer was attached to the specimen with an acoustic couplant and a constant force clamp. The acoustic signals, received by the transducer, were preamplified, filtered from external noise, and amplified to a total gain of 92 dB. The signals were simultaneously fed into a counter which performs ringdown counting above a fixed threshold (1 volt) and into a distribution analyzer which performs the counting of acoustic events. The cumulative number of events, the cumulative number of counts, as well as the count-rate, were plotted as functions of load or strain.

3. RESULTS

The dependence of the acoustic emission parameters on grain size at different strain rates is shown in Table 3. The numerical results are presented as averages along with the variance of the means.

It is noteworthy that no acoustic emission whatsoever was detected during the unloading of the specimens.

Table 3 refers to an additional set of samples with a grain size of 40 μm that were heat-treated at 320°C for 24 hours. Count rate maxima were not obtained at the yield point, as was the case for all other sets of samples, but rather at plastic strains of 0.5-1.0%.

Figure 2 shows a typical behavior of stress cumulative events and count rates vs. strain. Figure 3 exhibits the acoustic count rate behavior with variation of grain size for a constant strain rate. The dependence of the acoustic emission variables (cumulative counts, count rate maxima, average counts per event) upon the grain size for two different strain rates, is presented in Fig. 4. The differences in count rate behavior for the 40 μm grain size samples is shown in Fig. 5.

A decrease in the yield stress, σ_{yp} , is observed with increased grain size, in agreement with the Hall-Petch relationship. In addition, prolonged annealing and decreased strain-rates reduce the yield stress in general.

The numerical results presented in Table 3 show a large amount of scatter in almost all of the acoustic emission parameters: cumulative events, cumulative counts and count-rate maxima. Similar scatter is reported in other studies [5], and impedes any phenomenological conclusion based on such results. However, the computed $\Sigma C/\Sigma E$ parameter (average

number of counts per acoustic emission event), which is a measure of the energy of the acoustic event [6] shows much less scatter and is therefore more reliable.

The $\Sigma C/\Sigma E$ parameter attains a peak value at a grain size of 55 μm , so do the cumulative counts and the maximum count rate, when all specimens were strained at a rate of $3.3 \times 10^{-3} \text{ sec}^{-1}$. Similar peak values of all acoustic emission parameters appear also at a strain rate of $6.6 \times 10^{-3} \text{ sec}^{-1}$, but for a somewhat larger grain size, namely, 70 μm (Fig. 4). The average number of counts per event was found to be much higher for the specimens with the 40 μm grain size, heat-treated at 320°C for 24 hours. This behavior was observed for both strain rates. In general, the acoustic emission activity was much more pronounced in the long-annealed specimens, by almost two orders of magnitude.

The count rate dependence on the grain size and on the heat treatment as depicted in Figs. 3 and 4, shows the following salient features:

- a) Maximum count rate is always attained at the yield point
- b) The larger the grain size, the more extensive is the acoustic emission activity in the plastic range of deformation
- c) Prolonged anneals lead to acoustic emission activity beyond the yield point, up to 1.5% of plastic strain (Fig. 5).

Increasing the strain rate invariably leads to increased acoustic activity. This behavior is observed for all emission parameters, namely cumulative counts, cumulative events, maximum count rate, and average counts per event, as shown in Table 3 for the 70 μm grain size specimens at four different strain rates.

4. DISCUSSION

Possible mechanisms causing the observed acoustic emissions during plastic deformation are:

- Dislocation slip, or Luders band growth [1]
- Dislocation unpinning, or breakaway from pinning points [2]
- Activation of dislocation sources [5,7]
- Twinning [8].

Grain-boundary sliding has already been demonstrated not to contribute to acoustic emission [9,10].

Grain-size has the effect of increasing the mean free path for dislocation movement. If, according to Gillis [1], an acoustic event is associated with the growth of a deformation band within a single grain, the emission count rate should be proportional to the total number of grains. This means that at constant strain rate and specimen volume, the count rate should increase with decreasing grain size. This is contradictory to the present experimental results for Al, as well as for polycrystalline Cu [11].

If dislocation breakaway from pinning points is the main source for acoustic emission, there is no apparent correlation between this source factor and the strain-rate dependence of the acoustic activity. Moreover, high purity copper specimens of 70 μm grain size appeared to be by an order of magnitude more active acoustically [11] (at the same strain rate) than the 70 μm grain size Al-1100 specimens which have more pinning points due to the presence of 0.5% alloying elements.

The activation of dislocation sources is rendered responsible for the acoustic emission behavior in polycrystalline aluminum by Bill et al [5],

who report a peak activity for a certain grain size. This is in agreement with the results of the present investigation. Dislocations from an activated source are assumed to be able to sweep a whole grain in a single step. The larger slip area associated with the larger grain size permits a greater fraction of the activated source to be detected by the piezoelectric transducer. The rate of decrease in acoustic emission counts with a continuously increased grain size, beyond the peak value, can be attributed to the activation of dislocation sources in neighboring grains due to stress concentration at the ground boundary dislocation pile-ups. The number of these new sources is proportional to the grain boundary surface area, i.e., to $(\text{grain size})^{-1}$.

The model suggested by Bill et al [5] does not explain the strain rate dependence of the acoustic emission parameters. Such a dependence cannot be understood in terms of a simple source activation mechanism, unless kinematic considerations are taken into account.

Acoustic emission is the result of sudden stress relaxations which cause abrupt changes in the free flight motion of dislocations. Acceleration and deceleration of dislocations are a common feature during plastic deformation. This is a result of activation of dislocation source of breakaway from pinning points, arrest at grain boundaries or growth of dislocation pile-ups. Each of these source mechanisms for acoustic emission activity is well supported by appropriate experimental evidence and is therefore plausible. In polycrystalline material, all the mechanisms can be active simultaneously. A comprehensive approach, accounting for both strain rate and grain size dependences, would therefore be helpful. The kinematic treatment, presented thereafter is an attempt to formulate

an expression for the energy release during plastic deformation.

In a moving coordinate system, the strain energy density of a moving screw dislocation is [12, p.160]

$$W = \frac{\mu}{2\gamma^2} \left\{ \left(\frac{\partial u_z}{\partial x'} \right)^2 + \left(\frac{\partial u_z}{\partial y'} \right)^2 + \frac{v^2}{c_t^2} \left[\left(\frac{\partial u_z}{\partial x'} \right)^2 - \left(\frac{\partial u_z}{\partial y'} \right)^2 \right] \right\} \quad (1)$$

where

$$\gamma = \left(1 - \frac{v^2}{c_t^2} \right)^{\frac{1}{2}}.$$

When a screw dislocation is accelerated, a backstress is developed [12, p.188]

$$\sigma_{yz} = \frac{\mu b}{4\pi c_t^2} \int_{-\infty}^{t-b/c_t} \frac{dv(\tau)}{d\tau} \frac{d\tau}{t-\tau} = \frac{\mu b}{4\pi c_t^2} \bar{v} \ln \frac{c_t t}{b}. \quad (2)$$

Since $\sigma_{yz} = \mu \frac{\partial u_z}{\partial y}$, the energy per unit length of dislocation is

$$\frac{dW}{dL} = \frac{\mu b^2}{32\pi^2} \frac{\bar{v}^2}{c_t^4} \frac{\ln^2 \frac{c_t t}{b}}{\left(1 - \frac{\bar{v}^2}{c_t^2} \right)} \int_{-\infty}^{+\infty} dx \quad (3)$$

where the integral dx is along the mean free path Λ available for the screw dislocation to move. This mean free path is proportional to the average grain size and to the solute concentration. The strain-rate is proportional to the average velocity of the dislocation \bar{v} , and to the density of mobile dislocations N_M , which in turn, is proportional to the grain size, thus

$$\dot{\epsilon} = N_M b \bar{v} \quad . \quad (4)$$

Therefore, the energy per unit screw dislocation length per unit volume is

$$\frac{dW}{L} = \frac{\mu b^2}{32\pi^2} \ln^2\left(\frac{c_t t}{b}\right) \cdot \frac{\bar{v}^2}{c_t^2} \cdot \frac{\Lambda}{1 - \frac{\dot{\epsilon}^2}{N_M^2 b^2}} \quad (5)$$

Equation (5) implies the following:

- (a) Increasing the grain size causes dW/L to increase through the mean free path Λ , and to decrease through the dependence of the mobile dislocation density N_M . The relationship between N_M and grain size is not known. However, it is plausible to assume that the energy of a moving dislocation attains a maximum for a specific grain size.
- (b) An increase in the concentration of solute atom precipitates, or in the density of obstacles to dislocation motion, such as dislocation tangles and forests, cause dW/L to decrease.
- (c) Increasing $\dot{\epsilon}$, increases dW/L .

Although the energy per unit length has been primarily established for a moving screw dislocation, the behavior predicted by Eq. (5) can be generalized for all moving dislocations.

In the present experiment, the parameter $\Sigma C/\Sigma E$, i.e., the average energy per acoustic event, depends upon the grain size and strain rate in a similar manner as does the energy of the moving dislocation dW/L predicted by Eq. (5). The peak value, at both strain rates (Fig. 4) of

$\Sigma C/\Sigma E$ is due to opposing contributions, where Λ increases with grain size and N_M decreases with grain size. Increasing the strain rate invariably causes $\Sigma C/\Sigma E$ to increase as well.

The similarity in the behavior of the experimental parameter $\Sigma C/\Sigma E$ with the computed energy dW/L of the moving dislocations supports the assumptions made in the previous discussion.

The prolonged anneal (at 320°C for 24 hours) of the 40 μm grain size specimens is analogous to a homogenization treatment of the Al-1100. The solute content is reduced at the grain boundaries and sub-grain boundaries. External stresses will then cause the strains to be concentrated in the more ductile regions, and intercrystalline fracture may ensue. The lowering of the yield stress, accompanied by the enhanced acoustic activity and the increased value of $\Sigma C/\Sigma E$ parameter, may be due to such a sort of intercrystalline failure. The fact that the maxima of the acoustic count rates, for the 40 μm grain size specimens, were not observed at the yield point but rather at plastic strains of 0.5-1.0%, is consistent with the proposed mechanism. Figure 6 shows the morphology of a stressed sample, where intercrystalline failure is clearly apparent.

5. CONCLUSIONS

- A kinematic model, proposed to account for the strain rate and grain size dependences on plastic deformation of Al-1100, was found to be consistent with the experimental observations. The energy of moving dislocations during the deformation process depends upon the mean free path available for dislocation movement, upon the mobile dislocation density, and upon the strain rate.

The energy reaches a maximum value for a specific grain size.

- The average energy per acoustic event reaches a maximum value for the 55 μm grain size. It depends on the grain size and strain rate in the same manner as the energy of moving dislocation given by the proposed kinematic model. This acoustic parameter is therefore believed to reflect the kinematic characteristics of the plastic deformation of the alloy.

- Intercrystalline fracture produces acoustic emission signals distinctly different from those produced by dislocation-governed deformation yielding. The two deformation processes may be differentiated by the acoustic emission technique.

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TABLE 1. Chemical composition of Al-1100.

Element	Weight percent
Fe	0.44
Si	0.07
Cu	<0.01
Ga	<0.07
Zn	0.016
Mn	0.007

TABLE 2. Heat treatments and average grain size.

Average grain size (μm)	Recrystallization temperature ($^{\circ}\text{C}$)	Soaking time (hours)	Cooling mode
40 ± 2	320	24	air
40 ± 2	425	2	water
55 ± 5	530	3	water
70 ± 5	425	18	water
90 ± 10	530	24	water
120 ± 8	545	48	water

TABLE 3. Numerical results of acoustic emission in Al-1100.

Average grain size (μm)	Number of specimens in set	Strain rate $\dot{\epsilon}$ [sec^{-1}]	Cumulative event (ΣE)	Cumulative counts (ΣC)	Average counts per event ($\Sigma C/\Sigma E$)	Average count rate maximum \dot{c} [min^{-1}]	Average yield stress [$\text{kg}\cdot\text{mm}^{-2}$]
40 \pm 2	3	3.3×10^{-3}	7,900 \pm 700	50,500 \pm 10,500	6.3 \pm 0.8	750 \pm 150	1.55 \pm 0.01
	2	6.6×10^{-3}	9,300 \pm 200	197,000 \pm 26,000	21.3 \pm 3.3	780 \pm 150	1.80 \pm 0.05
40 \pm 2	3	3.3×10^{-3}	80 \pm 15	125 \pm 20	1.53 \pm 0.14	90 \pm 40	2.64 \pm 0.02
	2	6.6×10^{-3}	1,050 \pm 300	4,100 \pm 200	3.75 \pm 0.60	300 \pm 60	2.56 \pm 0.05
55 \pm 5	3	3.3×10^{-3}	700 \pm 350	2,250 \pm 1,450	3.01 \pm 0.7	475 \pm 250	2.50 \pm 0.02
	2	6.6×10^{-3}	1,100 \pm 400	4,200 \pm 1,800	3.63	725 \pm 5	2.66 \pm 0.05
70 \pm 5	1	1.6×10^{-3}	45	75	1.60	110	1.76
	3	3.3×10^{-3}	280 \pm 110	600 \pm 260	2.11 \pm 0.19	350 \pm 130	1.78 \pm 0.3
	1	6.6×10^{-3}	950	4,200	4.45	not avail.	2.12
	3	1.6×10^{-3}	1,500 \pm 700	17,000 \pm 800	11.21 \pm 0.10	610 \pm 50	not avail.
90 \pm 10	2	3.3×10^{-3}	170 \pm 120	280 \pm 200	1.63 \pm 0.03	150 \pm 60	1.32
	3	6.6×10^{-3}	500 \pm 200	1,000 \pm 700	1.93 \pm 0.54	380 \pm 20	2.27 \pm 0.18
120 \pm 8	2	3.3×10^{-3}	78 \pm 8	117 \pm 10	1.52 \pm 0.20	40 \pm 10	1.16 \pm 0.01
	2	6.6×10^{-3}	530 \pm 280	930 \pm 560	1.72 \pm 0.15	300 \pm 50	1.27 \pm 0.18

FIGURE CAPTIONS

Fig. 1. *Al-1100; typical grain sizes.*

Electrolytic etchant: ethanol and perchloric acid, 20 V/cm

Chemical etchant: HF, H₂SO₄, H₃PO₄, H₂O

Magnification: ×100, polarized light

Fig. 2. *Al-1100; typical dependence of stress, cumulative events and count rate vs. strain.*

Acoustic emission gain: 92 dB

Strain rate: $3.3 \times 10^{-3} \text{ sec}^{-1}$

Fig. 3. *Al-1100; count rate vs. grain size.*

Acoustic emission gain: 92 dB

Strain rate: $6.6 \times 10^{-3} \text{ sec}^{-1}$

Fig. 4. *Dependence of acoustic emission variables on grain size.*

a. Strain rate: $3.3 \times 10^{-3} \text{ sec}^{-1}$

b. Strain rate: $6.6 \times 10^{-3} \text{ sec}^{-1}$

Fig. 5. *Dependence of acoustic count rate on heat treatment.*

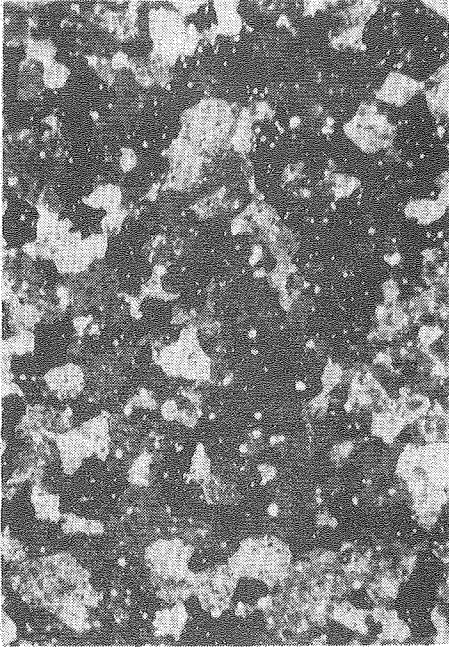
Count rate vs. strain, grain size: 40 μm

strain rate: $6.6 \times 10^{-3} \text{ sec}^{-1}$

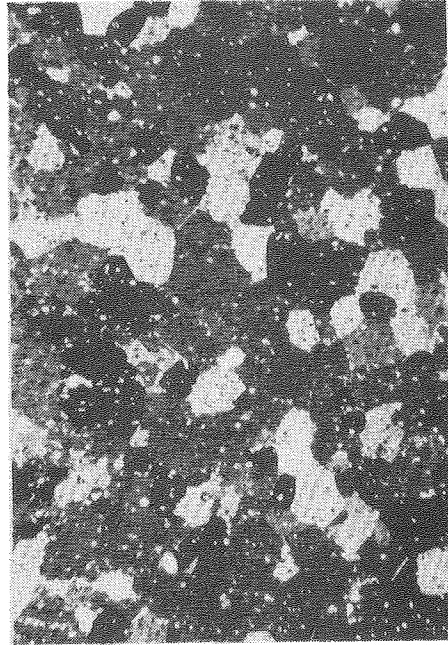
Fig. 6. *Stress effect on 40 μm grain size specimen of prolonged heat treatment.*

Intercrystalline failure at the arrow

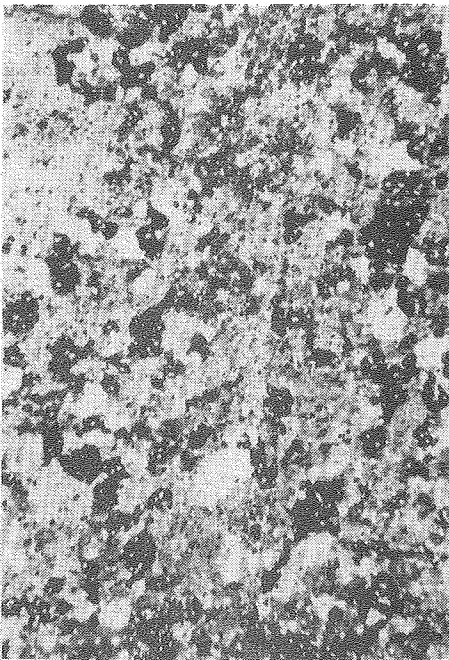
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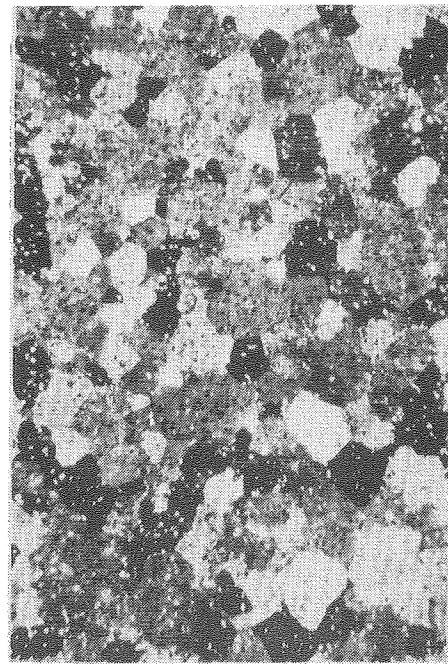
b. 55 mm



d. 120 mm



a. 40 mm



c. 90 mm

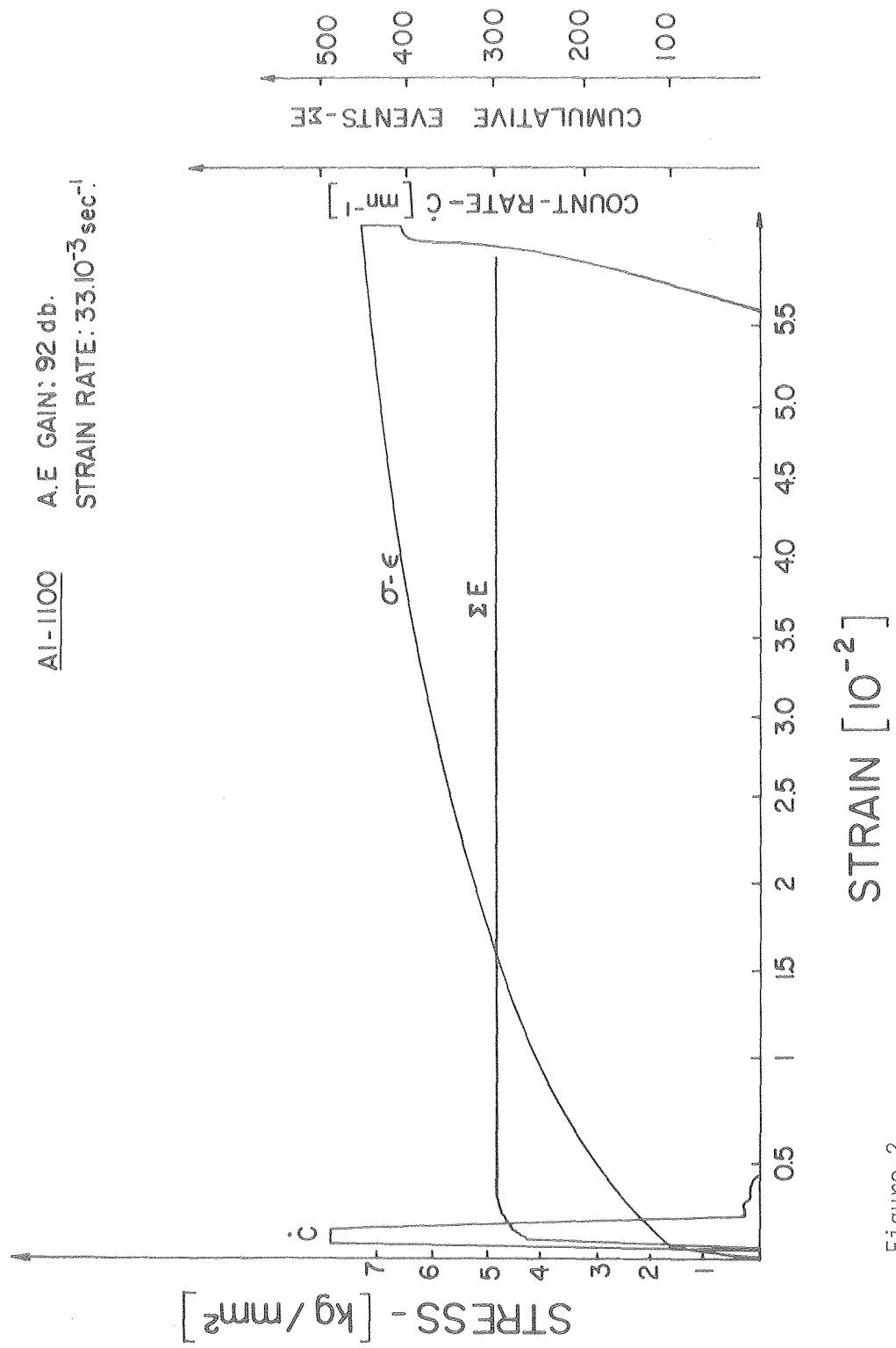


Figure 2

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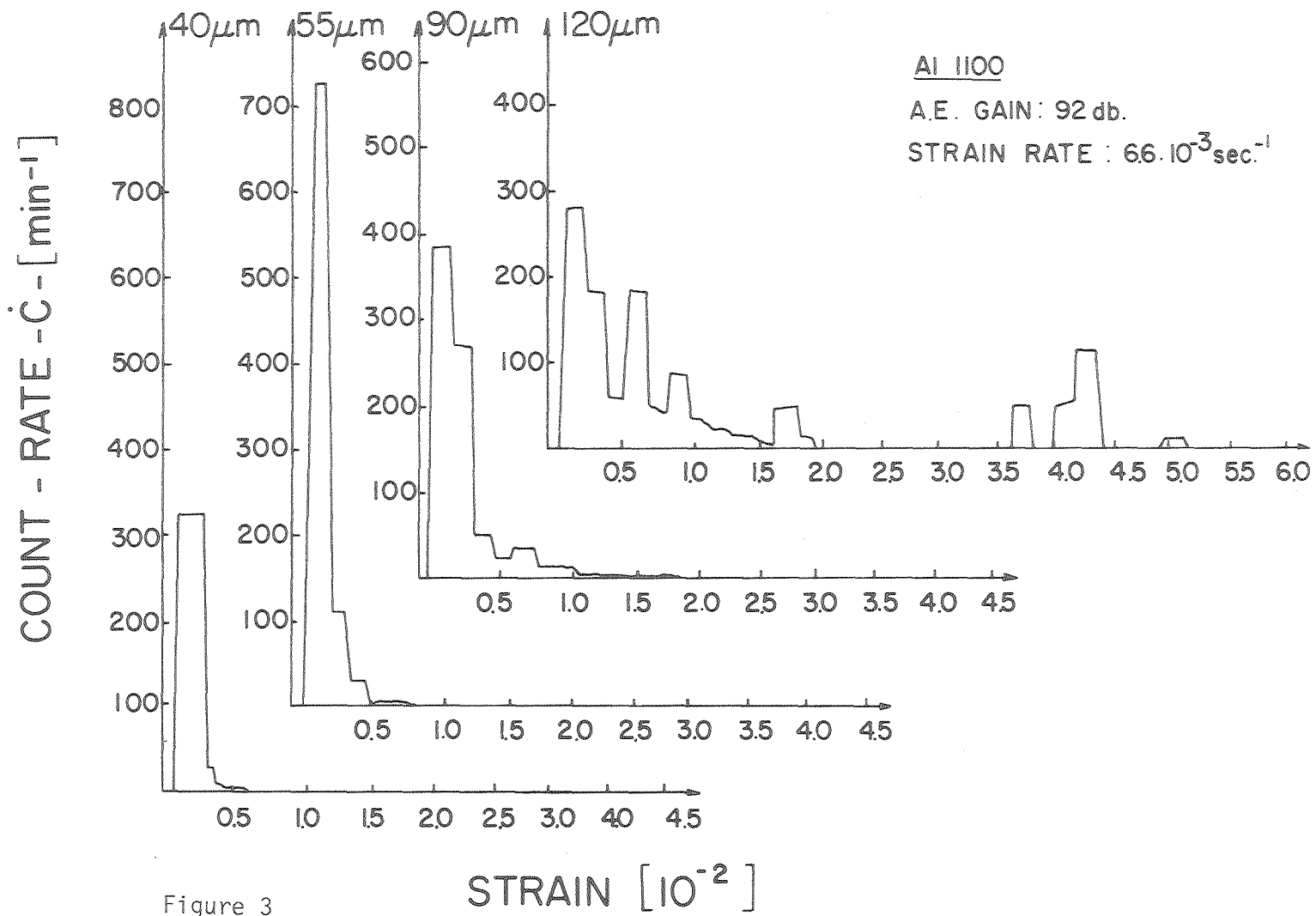


Figure 3

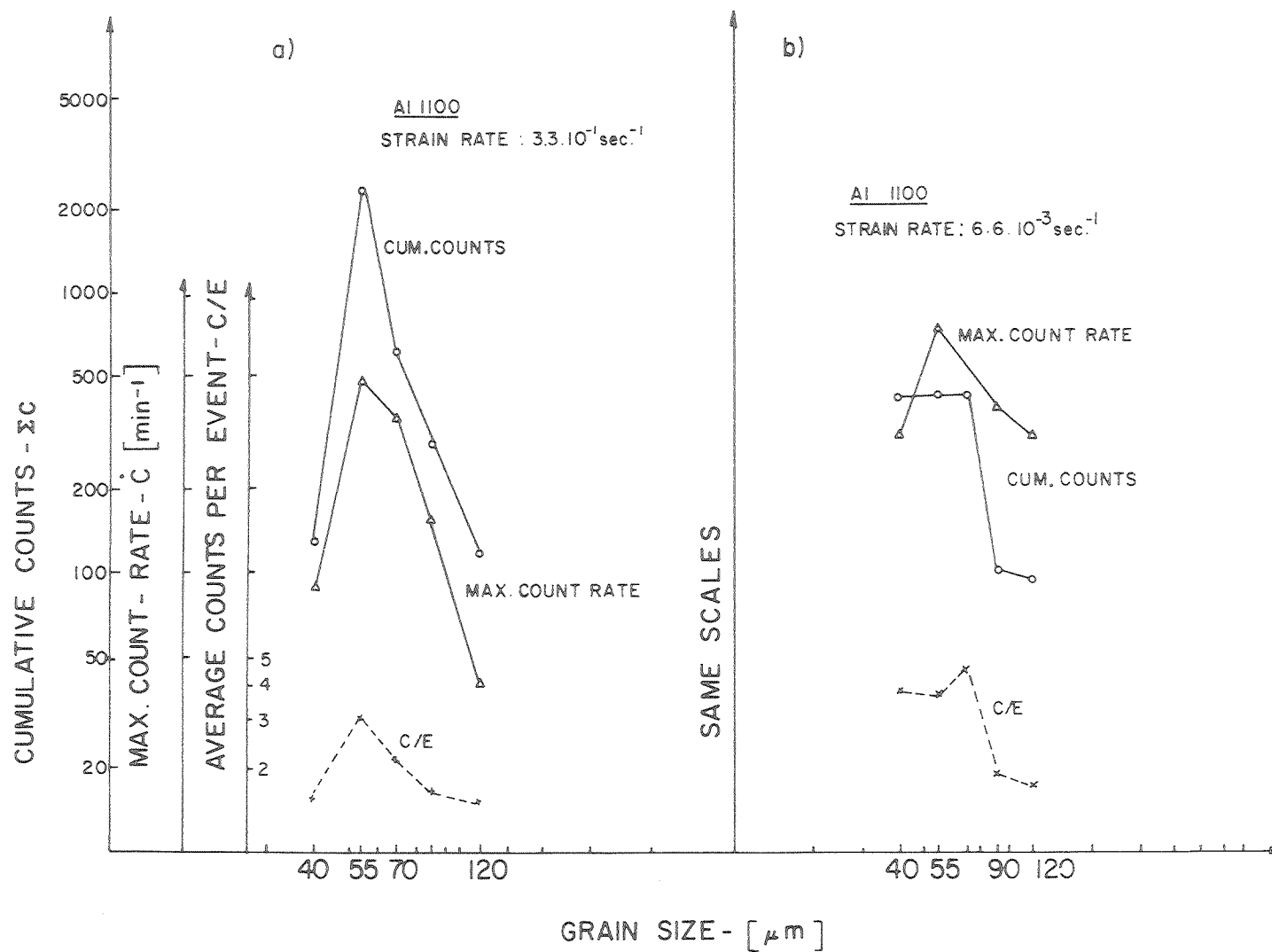


Figure 4

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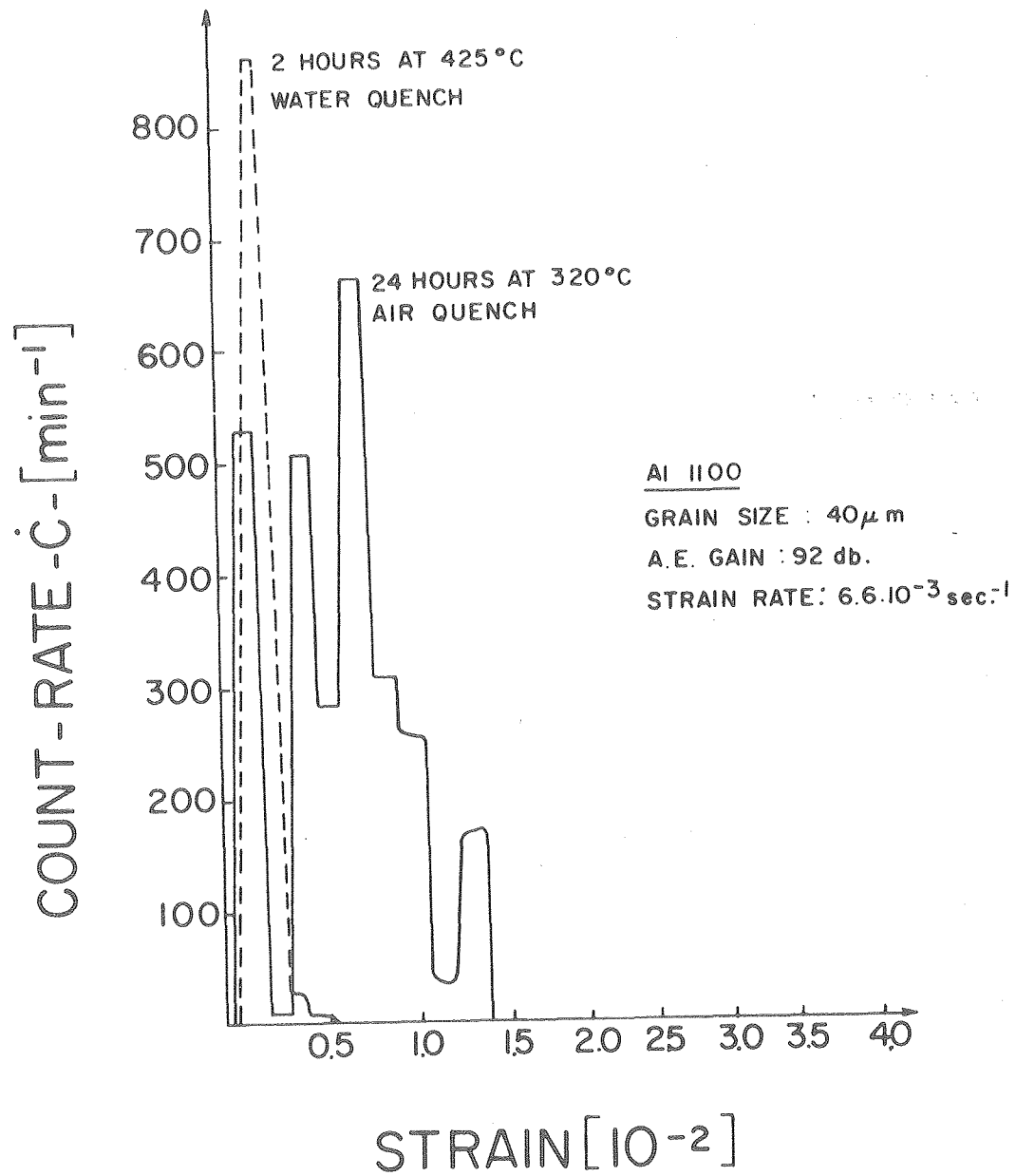


Figure 5

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